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REGULATION OF THERMAL SWEATING IN EVA SPACE SUITS

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INTRODUCTION

Astronauts on future extravehicular assignments in space, or on the surface of the moon and planets must be provided with microclimates compatible with life in, to say the least, hostile environments. Among the many functions which any space suit must fulfill are those of providing means for the regulation of temperature and humidity within physiological limits. The astronaut may at one time be required to work strenuously in a lunar crater while exposed to intense solar radiation, and at another time he may be at rest in a complete solar shadow. Such extreme environmental conditions present great difficulties to design of effective self-contained thermoregulatory systems.

It is the purpose of this paper to examine one aspect: that of the role of sweating in thermoregulation in space suits, and to discuss the ultimate disposition of any sweat secreted.

Existing extravehicular space suits provide thermal regulation first by isolating the astronaut from his surroundings with various insulation techniques, and second, by removing metabolic heat either by cold water circulated through tubes directly in contact with skin, as in the Apollo suits, or by recirculation of cooled and treated oxygen or oxygen mixed with an inert gas, as in the Gemini suits.

One of the design criteria for the liquid cooling system for the EVA hardsuit is to minimize secretion of thermal sweat (1)*. With chilled water circulating through a network of tubing in contact with the skin, Webb and Annis (2,3) have been able virtually to suppress sweating at work loads in excess of 900 k-cal/hr (3,570 Btu/hr.). They have set 100 gm/hr (0.22 lbm/hr) as a desirable upper limit for total moisture loss, including the insensible transpiration and evaporative losses from the lungs. Suppression of sweat to these low levels was recorded consistent with subjective acceptance of the cooling at the skin.

Recently Fanger (4,5), while a visiting professor at Kansas State University developed regression equations correlating thermal comfort with environmental parameters and observed physiological responses. For thermal comfort, substantial sweat rates are predicted at moderate work rates and above.

These equations are:

$$\bar{t}_s = 35.7 - 0.032 \frac{M}{A_{Du}} (1 - \eta) \text{ (kcal/m}^2\text{hr)} \quad (1)$$

$$\bar{S}_w = 0.42 A_{Du} \left(\frac{M}{A_{Du}} (1 - \eta) - 50 \right) \text{ (kcal/hr)} \quad (2)$$

where:

\bar{t}_s = mean skin temperature, °C.

M = metabolic heat production, kcal/hr.

* Underlined numbers in parentheses refer to corresponding numbers in the list of references.

A_{Du} = surface area, m^2 .

\bar{S}_w = mean heat loss by evaporation of sweat,
kcal/hr (1 gm evaporated absorbs approxi-
mately 0.58 kcal)

η = mechanical efficiency of human body (= 0 for
level walking and rest)

From equation (2), a man of average size walking on the level at the leisurely pace of 4 km/hr (2.5 mph) would sweat at a predicted rate of about the 100 gm/hr (0.22 lbm/hr) level. At 5.6 km/hr (3.5 mph) the predicted rate would be nearly 150 gm/hr (0.33 lbm/hr). Highest sustained work loads, on the order of 500 kcal/hr, (1,985 Btu/hr) would be expected to elicit about 300 gm/hr, (0.66 lbm/hr), consistent with thermal comfort. These predictions do not appear to be compatible with Webb's observations.

Because of the fundamental implications of the "no-sweat" concept in specifying thermoregulatory configuration of EVA suits, we have explored the question of sweat suppression in our laboratory in air and in a shower.

Air Environment Studies (6)

Young, healthy, male volunteers (two) were exposed to environments ranging from 13° to 24°C (55° - 75°F) at three levels of exercise: sitting, level treadmill walking at 4.0 and 5.6 km/hr (2.5 and 3.5 mph). These tasks elicited metabolic rates of about 100, 220 and 300 kcal/hr (397,873 and 1,190 Btu/hr) respectively.

Clothing was limited to athletic trunks, shoes and socks.

At ten minute intervals measurements were taken of skin temperature (thermocouples affixed to nine areas), heart rate, rectal temperature, and subjective thermal comfort. Each half hour the subject was transferred to a scale and total weight measured to ± 5 gms (± 0.01 lbm). Metabolic rate was determined twice each exposure by indirect calorimetry. Each exposure period lasted for 2 hours, unless discomfort of the subject dictated an earlier abort.

Subjects were able to perform the resting and 4.0 km/hr (2.5 mph) walking tasks comfortably at sweat rates less than 100 gm/hr (0.22lbm/hr). At our higher rate, which is not an excessive work load, both subjects exceeded the 100 gm (0.22 lbm) limit by 30 to 50 gm/hr (0.066 to 0.11 lbm/hr). It was possible to suppress sweating below the 100 gm/hr (0.22 lbm/hr) level at the higher metabolic rate, but the subjects were uncomfortably cool; and sometimes shivering was noted. Table I summarizes the findings.

It is interesting to note that data of this study fell within reasonable limits of Fanger's regression lines for those exposures which the subject reported "comfortable". All but two exposures where the subject expressed discomfort fell considerably below the regression lines. It appears that Fanger's model might be useful for predicting the amount of moisture which the life support system would have to remove at the several levels of

Table I.

Sweating Responses (average of two subjects) at Three Levels Of Exercise and Several Levels of Atmospheric Temperatures

Air Temp.	Sitting		Walking			
	Sweat gm/hr.	Comfort Vote	4.0km/hr Sweat gm/hr.	Comfort Vote	5.6km/hr Sweat gm/hr.	Comfort Vote
12.8°C (55°F)			90	cold	70	cool
15.5°C (60°F)			60	cool	95	cool-comf.
18.2°C (65°F)	50	cold	75	comf.	140	comf.
21°C (70°F)	45	cool-comf.	80	comf.		
24°C (75°F)	20	comf.				

metabolic heat production foreseen for extra-vehicular activities.

In Table I. , the data for rest (sitting) seem to display an inverse relationship between sweating and air temperature. The lowest sweat rates were at 24°C (75°F) when the subjects voted "comfortable". Sweating increased somewhat as air temperature dropped. This was consistent in the two subjects and perhaps reflects reaction to the cold: shivering, etc. It is again noted at 12°C (54°F) while walking at 4.0 km/hr (2.5 mph) where the subjects were quite cold. This fact perhaps indicates that there is optimal cooling at the skin; over-cooling may defeat the purpose, besides creating unnecessary discomfort of the subject.

Shower Studies (7)

A drenching shower was created with twelve shower heads located on the four corners of the exercise area in such an arrangement as to provide minimum water impact upon impingement on the body surface. A 50 gpm (189 l/min) capacity pump provided the primary shower circulation. The bottom portion of the shower stall served as reservoir and held approximately 100 gallons (378 l) of water. The primary means of temperature control consisted of a small secondary water loop, powered by a separate pump, through a thermostatically controlled, 1500 watt (5,120 Btu/hr) hot water heater. For cooling purposes cold tap water was bled into the reservoir. The usual operation involved the addition of slightly more cold water than that required to compensate for the heat gains in the system; thus, temperature regulation was obtained automatically from the heater.

The volunteer subject was dressed in a thin waterproof garment to prevent suppression of sweating by direct contact with water (8). The suit was clamped tightly around the subject's torso and limbs to provide better contact with the skin. The head was covered with hoods open at the bottom to allow for breathing. With this arrangement, essentially uniform cooling over the entire body could be achieved, serving the purpose of the experiment without the complexity of building a tubing network.

Exercise consisted of stepping on and off a 32 cm (1.05 ft) high step at a rate determined by timed light flashes. Sweat loss was determined by weighing the subjects before and after exercise in the dry, nude state.

The subjects were tested to determine their insensible sweat rates under thermally neutral conditions. It was assumed that they were losing moisture at this rate during the time between the actual weighings which was not exercise time. Thus the dressing time multiplied by the insensible sweat rate was subtracted from the subject's observed weight loss.

Four unacclimatized males between 22 and 43 were studied at two exercise rates. "Light" activity consisted of approximately 250 kcal/hr (992 Btu/hr) and "heavy" was about 333 kcal/hr (1,320 Btu/hr); which, in fact, is not really heavy work. Figure 1 shows the sweat rate versus shower temperature for subject "B" at the two exercise rates. The lowest point for these curves, and subsequent figures, represents essentially the coldest tolerable shower temperature for the subjects. At these temperatures, the subjects were cold, but managed to carry on for the period required. Sweat rates for subject "B" were suppressed to values approximating the desirable 100 gm/hr (0.22 lbm/hr) level; perhaps as high as 150 gm/hr (0.33 lbm/hr) at the higher work load.

As shown in Figure 2, however, subject "D" sweated at the rate of 500 gm/hr (1.1 lbm/hr) at the heavier work rate. This is

clearly well above the desirable level. It is interesting to note that he had the least tolerance to the cold water. The same subject "D" had one very high sweat rate of 480 gm/hr (1.06 lbm/hr) during "light" activity. The reason for this high value is thought to be partial acclimatization through concurrent participation in hot room studies. We have not as yet tested this man in the air environment; it would be interesting to see if he does maintain the high sweat characteristics in air.

Perhaps subject "D" has a physiologic makeup which precludes sweat suppression by skin cooling. These results challenge the wisdom of accepting at this time, without further study, the assumption that sweating can be adequately suppressed under all conditions and in all people. The possibility of thermal sweating should be accepted and provisions made to deal with it.

Alternative Methods of Metabolic Heat Removal

There is a possibility that more effective cooling and sweat reduction may be achieved by "zone cooling" the body instead of using a uniform coolant temperature. Although such a system would be more complicated because of the multi-zone control, the the exploration of its feasibility seems justified and it is under investigation currently.

The previous results suggest a fundamental question. Would it be feasible to permit the astronaut to thermoregulate largely

by sweating? This would substantially reduce the complexity of the life support systems. Control would be effected by man's precise thermal regulatory capacities. With a passive moisture removal system, such as the one described below, no pumps or fans would be needed. Consequently power requirements would be also reduced.

The astronaut would of course be under heat stress -- to a greater or lesser extent depending upon his level of activity. With proper radiative insulation, the heatload would be essentially only his metabolic heat production. Experience in industry has shown that man can withstand heat stress eliciting sweat rates up to a liter an hour for eight hours (9). This would be equivalent to working at a sustained rate of 500-600 kcal/hr (1,985 - 2,380 Btu/hr.). Only for short durations need this level be reached or exceeded. An adequate supply of drinking water to make up water lost through sweating would be a requirement of this system.

Cooling of the skin by the evaporation of sweat could be achieved by porous sublimator plates placed strategically a short distance away from the skin surface. The evaporated water vapor would condense on the inside surface of the sublimator plate while the ice formed within the plate would sublime from the outer surface into the vacuum of space. Such sublimator plates are used currently in life support systems in space suits for rejecting the heat from the coolant. Properly designed and located,

such sublimator plates would be largely self-regulating. Additional control could be effected by the astronaut by regulating the openings between the sublimator plates and the vacuum of outer space.

Refinements of the basic system could include a light undergarment for more uniform distribution of the moisture, and a manually operated water supply which could wet the undergarment to provide additional evaporative cooling without the need for excessive physiological strain to produce high rates of sweating.

The following calculations indicate the feasibility of such a system.

Consider the astronaut enclosed in a space suit where the conditions are specified as follows:

1. A skin area of $A = 1.25\text{m}^2$ (13.44ft^2) is exposed to sublimator plates located parallel to the skin surface at a mean distance of $l = 2 \text{ cm}$ ($0.79 \text{ in} = 0.0656 \text{ ft.}$).

2. The mean skin temperature is 35°C (95°F) and the mean sublimator plate inside surface temperature is 0°C . (32°F).

3. The space suit atmosphere is pure O_2 at $1/3$ atmospheres pressure with its temperature varying linearly from the skin to the sublimator plate.

The problem can be considered as simple diffusion of one component, water vapor, in a stagnant gas, oxygen; plus conduction of heat across the stagnant gas layer.

Assuming that both components behave as ideal gases, the molal mass flux is given by Stefan's equation (10):

$$\frac{N_{H_2O}}{A} = \frac{DP}{RTl} \frac{P_{H_2O, skin} - P_{H_2O, plate}}{P_{O_2,m}} \quad (3)$$

where:

N_{H_2O} molal flow rate

A skin area exposed

D mass diffusivity

P total pressure

R gas constant

T absolute temperature

l mass transport distance

P_{H_2O} partial pressure of water vapor

$P_{O_2,m} = (P_{O_2, plate} - P_{O_2, skin}) / \ln (P_{O_2, plate} / P_{O_2, skin})$,
logarithmic mean partial pressure of oxygen.

The mass diffusivity can be estimated from Gilliland equation

(11) to be:

$$D = 3.82 \text{ ft}^2/\text{hr} = 0.986 \text{ cm}^2/\text{sec}$$

The values for the other parameters are:

$$A = 1.25 \times 10^4 \text{ cm}^2$$

$$P = 0.3333 \text{ atm.}$$

$$R = 82.05 \text{ cm}^3\text{atm/g mole } ^\circ\text{K}$$

$$T = 290.5^{\circ}\text{K}$$

$$l = 2 \text{ cm}$$

$$P_{\text{H}_2\text{O},\text{skin}} = 0.0555 \text{ atm}$$

$$P_{\text{H}_2\text{O},\text{plate}} = 0.0060 \text{ atm}$$

$$P_{\text{O}_2,m} = (0.3273 - 0.2778) / \ln (0.3273/0.2778) = 0.300 \text{ atm}$$

Substituting these values into equation (3) yields

$$N_{\text{H}_2\text{O}} = 1.422 \times 10^{-2} \text{ g mole/sec}$$

The latent heat of vaporization at the skin temperature of 35°C is

$$h_{fg} = 10.41 \text{ kcal/g mole}$$

Therefore, the heat removed from the skin surface by evaporation becomes

$$Q_e = N_{\text{H}_2\text{O}} h_{fg} = 0.148 \text{ kcal/sec} = 533 \text{ kcal/hr} = 2,120 \text{ Btu/hr}$$

There is also heat conduction across the essentially stagnant gas layer which can be calculated from Fourier's equation

$$Q_e/A = k \frac{T_{\text{skin}} - T_{\text{plate}}}{l} \quad (4)$$

Since the gas is almost all oxygen, let

$$k = 0.0148 \text{ Btu/hr ft}^{\circ}\text{F} = 2.2 \times 10^{-4} \text{ kcal/hr cm}^{\circ}\text{C}$$

Thus,

$$Q_c = 48.2 \text{ kcal/hr} = 192 \text{ Btu/hr}$$

The total heat transferred is

$$Q = Q_e + Q_c = 581 \text{ kcal/hr} = 2,310 \text{ Btu/hr}$$

which is quite adequate for the maximum sustained metabolic heat loads although it is below the expected maximum short duration metabolic rates. Since such transient heat loads cannot and should not be removed instantaneously, the deficiency can be made up over an extended period of time after the heavy exercise has occurred. The thermal regulation would be very similar to that experienced by people working in a dry but very hot climate. The skin to plate distance could also be reduced somewhat from the assumed 2 cm. Therefore, the scheme seems quite feasible from the standpoint of heat removal.

Conclusions

In this paper, the problem of metabolic heat removal in EVA space suits has been examined with special emphasis on the regulation of sweat rates. It has been found that with some people sweat secretion could not be reduced to a minimal level of about 100 gm/hr (0.22 lbm/hr) with uniform direct contact cooling of the skin. These results suggest that some form of sweat removal mechanism may have to be incorporated in all space suits unless

1. It can be determined by extensive physiological tests that the astronaut is not the "sweating" type; or
2. Alternative methods of metabolic heat removal can be found.

Two possibilities have been discussed in the paper. The first was the suppression of sweat by "zone cooling". The second was the completely opposite concept of utilizing the astronaut's own thermoregulatory system and provide cooling by the evaporation of sweat, employing porous sublimator plates for the removal of moisture.

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List of Figures

Figure 1. Comparison of sweat rates during "light" (open circles) and "heavy" (solid circles) activities of subject B.

Figure 2. Variation of sweat rates with water temperature during "heavy" activity.

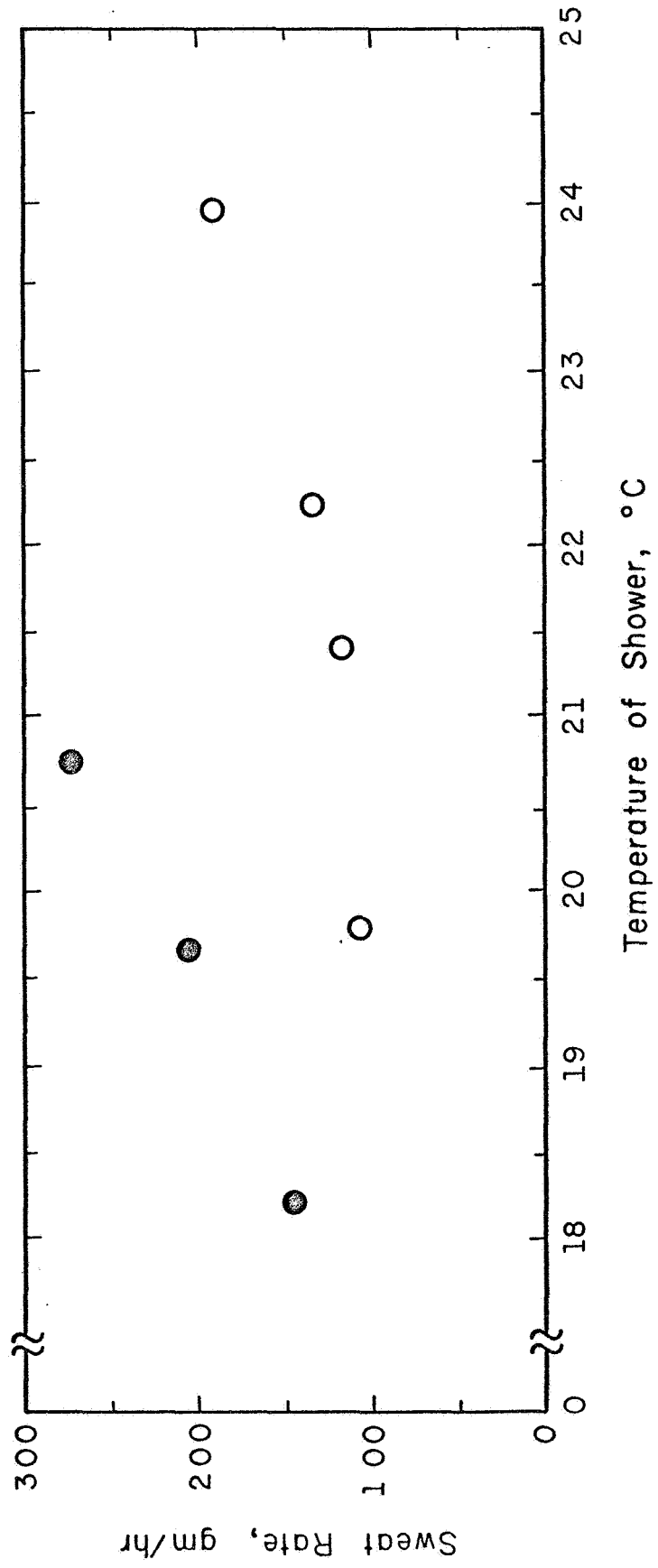


Fig. 1

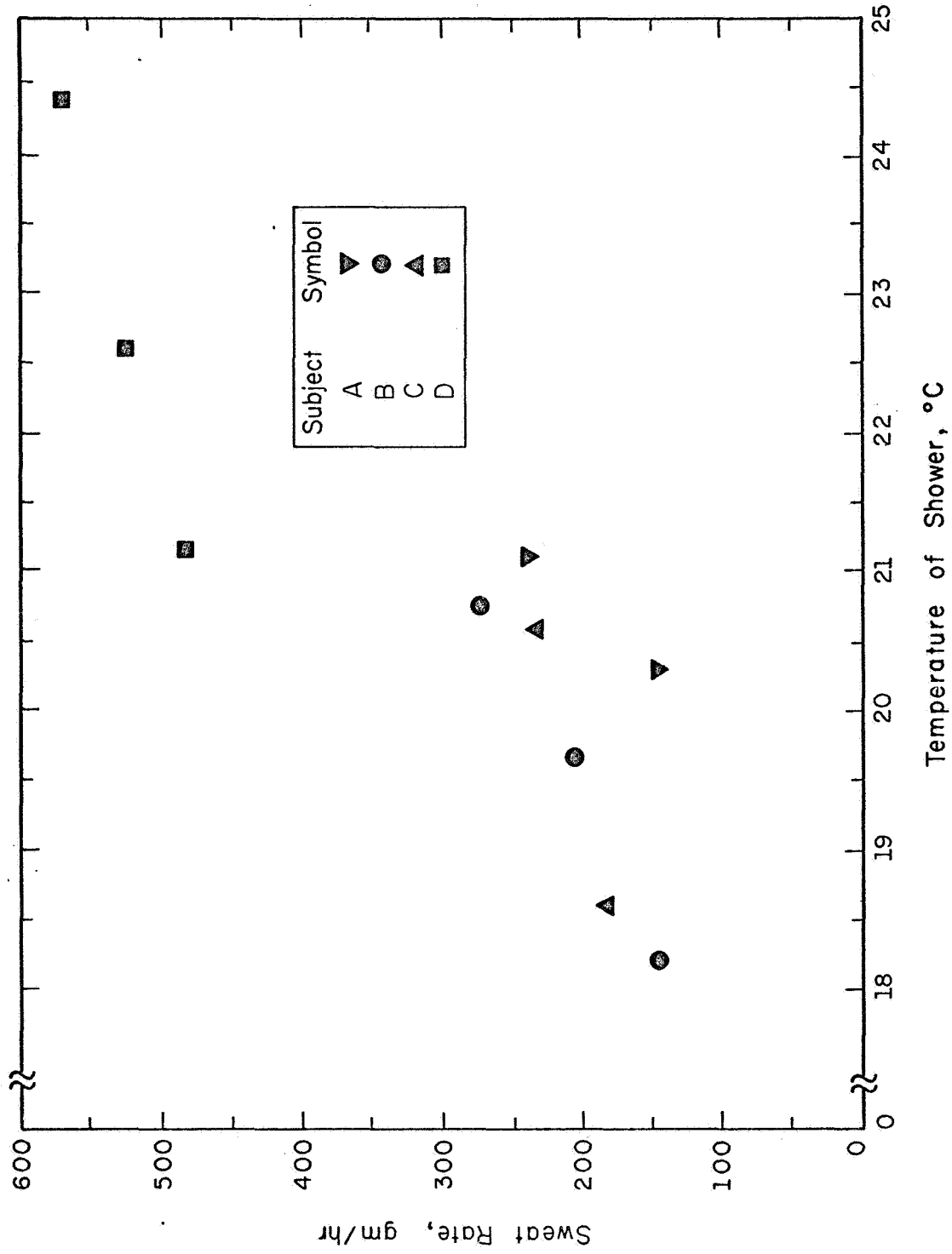


Fig. 2